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A 140 GHz High Efficiency Slotted Waveguide Antenna using a Low Loss Feeding Network

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***Abstract*—This letter proposes a 140 GHz high efficiency slotted waveguide antenna with a low loss feeding network. The feeding network consists of the feeding slot, the over-mode cavity and the coupling slots, which provides the same-magnitude but alternating-phase excitations for the slotted parallel-plate waveguide array. The alternating-phase excitations are used to implement virtual electric walls for replacing the physical metal walls of the conventional waveguides, which reduces the loss from the metal walls. Hence, the antenna efficiency is improved significantly. Moreover, the implementation challenges of the tiny metal sidewalls of the THz waveguides are avoided. The proposed low loss feeding network has a compact size, which integrates the power divider and phase shifter together. By using the computer numerical control metal-milling technology, an 8 × 8 slot array with the proposed feeding network is designed and fabricated, which has a fractional bandwidth of 10.17%, i.e. from 132 to 146.15 GHz. Experimental results show that the radiation and aperture efficiency of the prototype can be as high as 93.4% and 73.2%, respectively. The measured antenna has a peak radiation gain of 24.59 dBi @ 137.5 GHz, and a flat in-band gain. The proposed antenna provides a promising solution to develop high efficiency upper millimeter-wave and sub-terahertz (THz) applications.**

***Index Terms*—140 GHz, alternating-phase excitations, high efficiency antenna, over-mode cavity, slotted waveguide array, virtual electric walls.**

I. Introduction

Recent years have witnessed the prosperous development of terahertz (THz) technology in applications due to its wideband available spectrum and high range resolution, such as high speed communication system [1], precision radars [2] and radio astronomy [3]. As a key component of the THz wireless system, a few types of THz antennas have been investigated in recent years, such as the 120 GHz hollow-waveguide slot array [4], the 140 GHz large-scale circular-polarized array antenna [5], the 140 GHz LTCC substrate integrated waveguide (SIW) slot antenna array [6]-[8], and the 400 GHz folded reflectarray [9]. Among them, the slotted waveguide array is attractive due to its compact size and planar form [4]. However, at the THz frequency band, the design of the slotted waveguide array faces a few challenges: 1) The relatively low radiation efficiency caused by the conductor loss of the complicated feeding network when a large-scale array is desired; 2) the high milling cost for implementing the tiny metal sidewalls of the THz waveguide, which have a thickness of a few micrometers and a large ratio of height to width.

The high-order-mode technique has been reported at microwave and millimeter-wave band [10]-[16] to improve antenna efficiency. A high radiation efficiency over 80% is achieved in [10] [11]. Nevertheless, as the operating frequency increases and the scale of the array becomes larger, the radiation efficiency drops quickly due to the dramatically increased conductor and dielectric losses, for example, from 92% at 32.2 GHz [11] to around 41% at 94 GHz [12] [13]. To avoid the conductor loss from the metal sidewall of the conventional waveguide, parallel-plate waveguide (PPW) technique has been reported with an alternating-phase feeding network in [14]-[16]. Among them, the alternating-fed slotted waveguide antenna is attractive for developing THz antennas [14]. However, it requires a sophisticated and tiny feeding structure which is hard to be fabricated at THz band, and its operating frequency bandwidth is relatively narrow.

This paper reports a wideband high efficiency antenna for D-band applications. A compact low loss feeding network based on the slotted over-mode cavity is proposed to provide same-amplitude but alternating-phase excitations for the parallel placed slotted waveguides. Then, virtual electric walls (VEWs) are generated between adjacent slotted waveguides. Consequently, the conductor loss from metal sidewalls is avoided, which is helpful to improve the radiation efficiency. Moreover, since the tiny metal sidewalls between slotted waveguides are removed, the fabrication complexity and cost are reduced significantly. The design principle is presented in Section II, and a 140 GHz 8x8 slotted array is fabricated and measured in Section III. Experimental results show that the measured prototype has a gain over 24 dBi and a radiation efficiency over 83% within operating frequency band. Finally, conclusions are drawn in Section IV.

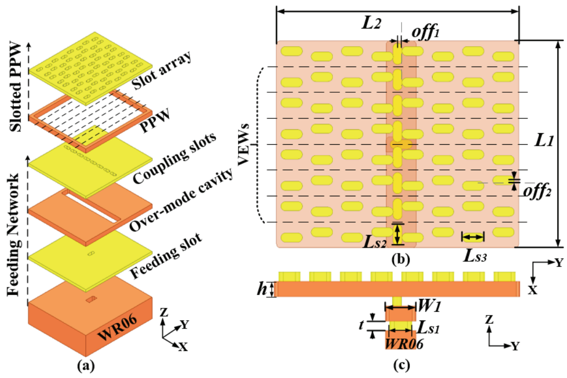

Fig.1. Configuration of the proposed 8×8 slotted waveguide antenna. (a) 3D structure; (b) top view (xy-plane); (c) front view (yz-plane).

II. Antenna Design

As illustrated in Fig. 1, the proposed antenna is composed of eight parallel placed slotted waveguides and a feeding network based on the slotted over-mode cavity. The slotted over-mode cavity is adopted as the center feeding network for the slotted waveguide array, which has same-amplitude but alternating-phase excitations. As a result, a VEW is generated between two adjacent parallel placed slotted waveguide, and the physical metal waveguide sidewall can be removed. Then, the parallel placed slotted waveguides can be evolved as the slotted parallel-plate waveguide (PPW). In addition, since the slotted over-mode cavity functions like a series power-divider with alternating phase, it has a much compact size than the parallel feeding network [4].

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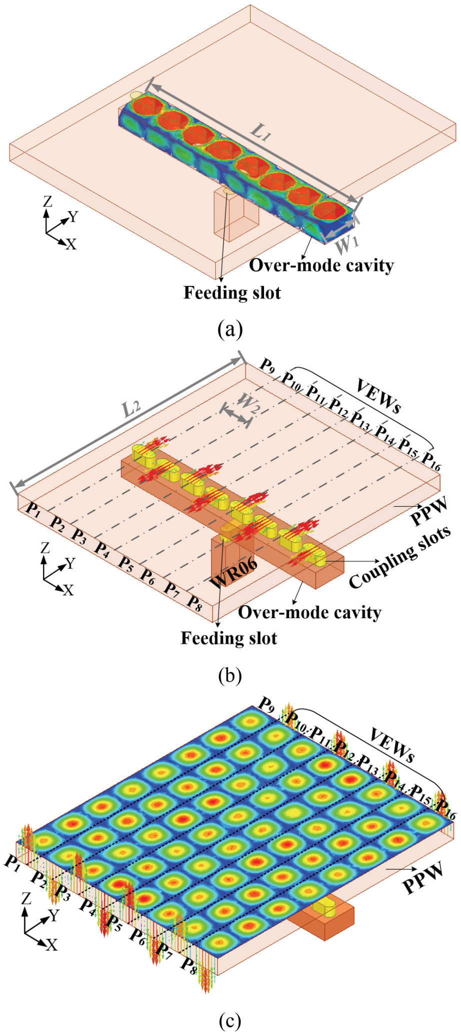

Fig.2. Electric field distributions at 140 GHz. (a) Over-mode cavity; (b) coupling slots; (c) PPW.

A. Compact Alternating-Phase Feeding Network

The alternating-phase feeding network is depicted in Fig. 2(a), which employs a slotted over-mode cavity. A standard THz waveguide is used to feed the over-mode cavity through a center slot underneath the over-mode cavity, and eight coupling slots along X-axis are etched on the top surface of the over-mode cavity for realizing an eight-way power-divider with alternating phase. Since the feeding slot is etched at the center of the over-mode cavity, only even-order resonating modes can be excited, which is determined by the width (W_1) and length (L_1) of the over-mode cavity. To obtain eight-way excitations for the slotted PPW array, the $TE_{8,1,0}$ mode is selected in this work. Then, the length (L_1) is designed as $4\lambda_{g1}$ @ f_0. According to (1)-(3), when W_1 is selected as 1.64 mm, λ_{g1} and L_1 should be 2.82 mm and 11.28 mm, respectively. The electric field distributions in the over-mode cavity (W_1 = 1.64 mm, L_1 = 11.28 mm) is displayed in Fig. 2(a) when the feeding network is seamlessly integrated with the PPW.

$$\lambda_0 = \frac{c_0}{f_0} \tag{1}$$

$$\lambda_{g1} = \frac{\lambda_0}{\sqrt{1-(\frac{\lambda_0}{2W_1})^2}} \tag{2}$$

$$L_1 = 4\lambda_{g1} \tag{3}$$

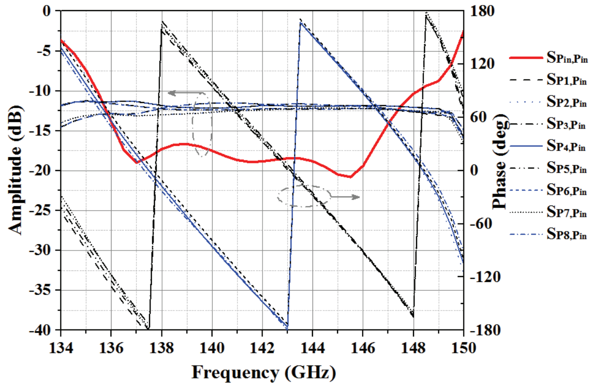

Fig. 3. Simulated S-parameters of the structure illustrated in the Fig. 2. (W_1= 1.64 mm, L_1= 11.28 mm, L_2= 13.2 mm, h= 0.82 mm, t= 0.5 mm, L_{s1}= 1.21 mm, off_1 = 0.2 mm and L_{s2} = 1.15 mm)

where f_0 is 140 GHz, c_0 is the velocity of light in vacuum, λ_0 is the wavelength @ f_0 in vacuum, and λ_{g1} is the guide wavelength @ f_0 in the over-mode cavity.

For achieving a uniform feeding, all eight coupling slots of the slotted over-mode cavity are designed to have the same length (L_{s2}) and offsets (off_1). And the distance between adjacent coupling slots is $\lambda_{g1}/2$. Hence, eight coupling slots are excited synchronously by the $TE_{8,1,0}$ mode. Then, adjacent coupling slots have the same coupling magnitudes but alternating phases, as shown in Fig. 2(b). Consequently, the electric fields on the sidewalls of adjacent waveguides, denoted by the black dash lines in Fig. 2(c), are zero. Therefore, the VEWs are generated, and conventional metal sidewalls of the parallel placed waveguides can be removed.

The simulated amplitude and phase responses of the proposed feeding network are plotted in Fig. 3. Its -10 dB reflection coefficient bandwidth is approximately 9.2% (135.5-148 GHz), the amplitude of transmission coefficients for each output is about -12 dB, and a 180-degree phase difference between two adjacent ports is obtained.

B. 8×8 Slotted PPW Array

To excite the slotted PPW in Fig. 1 by the proposed feeding network, the equivalent width (W_2) of each parallel placed slotted waveguide should be L_1/8 ($\lambda_{g1}/2$), where the L_1 = 11.28 mm is the length of the over-mode cavity. In this work, each slotted waveguide has eight radiation slots along Y-axis. Hence, the length (L_2) of the slotted waveguide is $4\lambda_{g2}$, where λ_{g2} is the guided wavelength of the slotted waveguide at center frequency f_0. According to (4)-(6), λ_{g2} and L_2 are calculated as 3.3 mm and 13.2 mm, respectively.

$$W_2 = \frac{L_1}{8} = \frac{\lambda_{g1}}{2} \tag{4}$$

$$\lambda_{g2} = \frac{\lambda_0}{\sqrt{1-(\frac{\lambda_0}{2W_2})^2}} \tag{5}$$

$$L_2 = 4\lambda_{g2} \tag{6}$$

A uniform 8x8 slotted PPW array is designed for demonstration. Considering the available metal milling precision, all the slots are designed with a width of 0.5 mm, and the distance between adjacent radiation slots is 1.65 mm ($\lambda_{g2}/2$). Then, the initial offset and length of the radiation slots are extracted using the slotted array synthesizing theory [17]. Finally, the optimized geometries including the lengths (L_{s3}) and offsets (off_2) are obtained by adjusting those initial geometries using the full-wave simulator HFSS.

Table I lists the dimensions of the proposed 140 GHz 8x8 slotted PPW array antenna. As described in Fig. 4, the simulated fractional

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TABLE I

DIMENSIONS OF THE 8×8 SLOT ARRAY ANTENNA (UNIT: MM)

W_1	L_1	L_2	h	t
1.64	11.28	13.2	0.82	0.5
L_{s1}	L_{s2}	L_{s3}	off_1	off_2
1.21	1.15	1.16	0.2	0.15

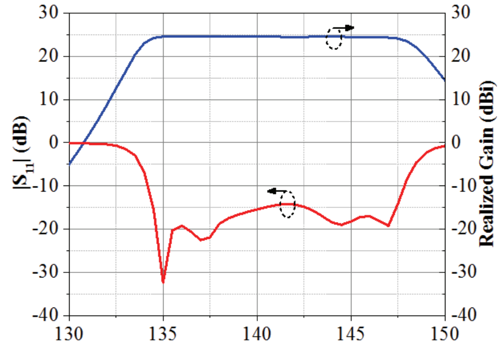

Fig. 4. Simulated results of 8×8 slotted waveguide antenna.

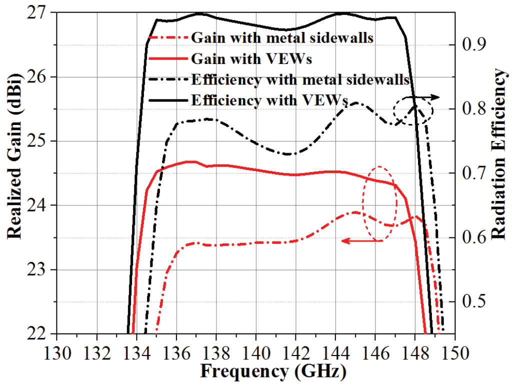

Fig. 5. Simulated gains and radiation efficiencies of the proposed antenna with metal sidewalls and VEWs. (The simulated radiation efficiency is calculated as the ratio of simulated realized gain to simulated directivity.)

bandwidth for |S11| < -10 dB is 9.73% (134-147.7 GHz), and a very flat gain response is obtained as well. From 135 to 147 GHz, the radiation gain fluctuation is smaller than 0.4 dB. The simulated gains and radiation efficiencies of proposed antennas with metal sidewalls and VEWs are illustrated in Fig. 5. It can be seen from Fig. 5 that by adopting proposed feeding network, the gain is improved from 23.5 dBi to 24.5 dBi at 140 GHz, and the radiation efficiency is improved from 75% to 93%,.

III. FABRICATION AND MEASUREMENTS

The designed prototype is fabricated by using the conventional CNC metal-milling technology, and its photographs are demonstrated in Fig.6. In addition, the measurement setup in the THz chamber is presented in Fig. 7. As shown in Fig. 8, the measured -10 dB reflection coefficient bandwidth is 10.17% (132-146.15 GHz), which has a 1.26% frequency offset to low frequency comparing with the design. The small frequency shift is mainly caused by the fabrication tolerance. Fig. 9 presents the reflection coefficients with different dimensional deviations of the proposed antenna. Generally, the operating frequency shift is resulted by the variation of the coupling slots length (L_{s2}) and the over-mode cavity length (L_1). Fig. 10 shows the measured gain and radiation efficiency, which is calculated as the ratio of the measured gain to simulated directivity. The measured gain is between 23.5 and 24.59 dBi within 132-146.15 GHz. Additionally, the

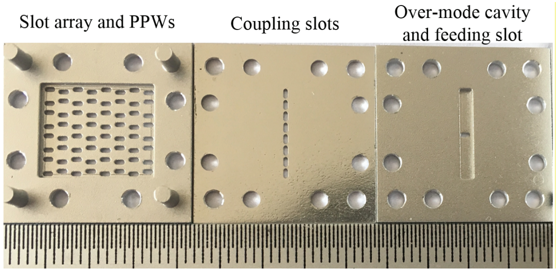

Fig. 6. Photographs of the 8×8 prototype.

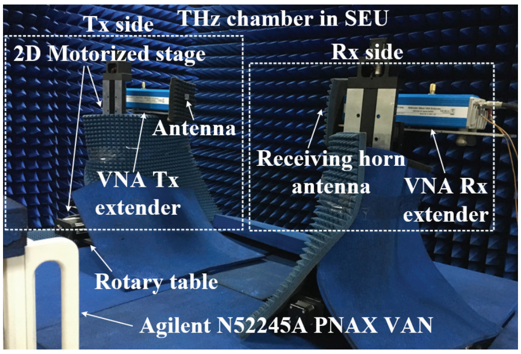

Fig. 7. Measurement setup.

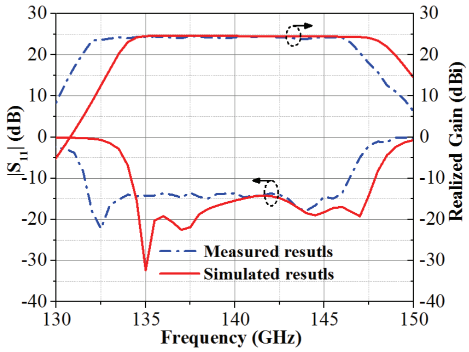

Fig. 8. Comparison between the measured and simulated reflection coefficients and radiation gains of the 8×8 prototype.

measured maximum radiation efficiency and aperture efficiency are 93.4% at 145.5 GHz and 73.2% at 137.5 GHz, respectively. Here, the aperture efficiency is defined as $\frac{G\times\lambda^2}{4\pi A}$, where A is the radiation aperture area, λ is the wavelength, and G is the measured gain. As can be seen in Fig. 10, a small fluctuation of 0.5 dB can be found for the in-band measured gain. This is due to the following reasons: 1) Unstable output power of the THz sources. At such high frequency band, the output power of the THz source is pretty weak and it is hard to obtain a stable output power within a wide frequency band. 2) The small shaking of the rotary table. The small shaking may lead to a fluctuation of the measured gain at THz band. The measured and simulated radiation patterns of the prototype are compared in Fig. 11. In general, the measured radiation patterns agree well with the simulated ones.

A summary of the proposed antenna and the up-to-date high frequency planar arrays are presented in table II. Generally, all reported antennas require a sophisticated feeding network. In addition, tiny structures have to be fabricated for the antenna at the high operating frequency above 100 GHz. Consequently, not only the cost but also the loss from the feeding network of a high frequency array increase dramatically. By adopting proposed feeding network, the

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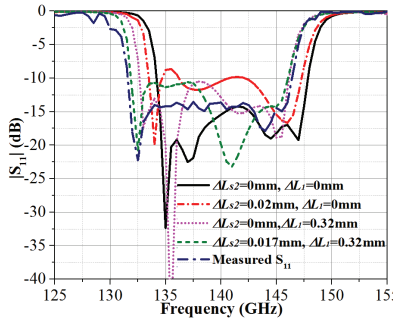

Fig. 9. Error analysis of the dimensional deviations.

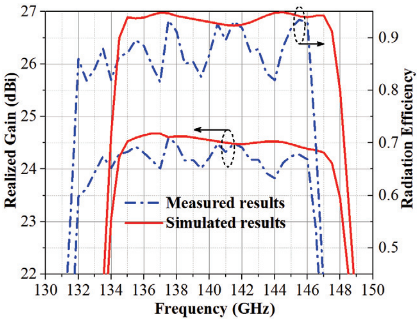

Fig. 10. The measured gain and radiation efficiency.

feeding network loss and the cost can be reduced significantly. Thus, the proposed slot array has the highest radiation and aperture efficiencies and smallest in-band gain fluctuation among compared high frequency antennas.

IV. Conclusions

A high efficiency slotted waveguide antenna is reported in this paper by using a compact slotted over-mode cavity feeding network. The proposed slotted over-mode cavity can realize the same-amplitude but alternative-phase excitations for the proposed antenna. Then, VEWs are generated between adjacent parallel placed slotted waveguides, which can be used to replace the physical metal sidewalls. As a result, the fabrication challenge of the tiny metal sidewalls of THz waveguide is avoided, as well as its ohm loss. Consequently, the radiation efficiency is improved significantly. A 140 GHz 8x8 prototype is designed, fabricated and measured. Compared with the conventional parallel placed slotted waveguide antenna, the proposed antenna can improve the gain from 23.5 dBi to 24.5 dBi, and the radiation efficiency from 75% to 93%. The proposed antenna has a compact size, a high radiation efficiency and a low fabrication cost. Therefore, it provides a promising solution for THz wireless systems.

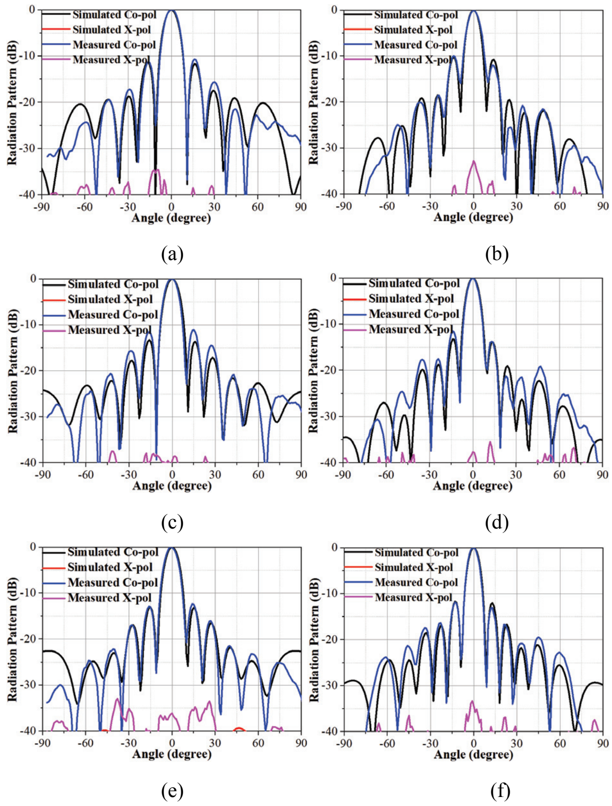

Fig. 11. The measured and simulated radiation patterns of the prototype. (a) E-plane and (b) H-plane at 135 GHz; (c) E-plane and (d) H-plane at 140 GHz; (e) E-plane and (f) H-plane at 145 GHz.

TABLE II
COMPARISONS BETWEEN PROPOSED AND REPORTED RELATED PLANAR ANTENNAS

Ref.	f_0	Size	Type	No. of Elements	Peak radiation/ aperture efficiency (%)	Imp. BW (%)	In-band Gain Variation (dB)	Gain (dBi)
[13]	94	6.5λ ×6.5λ	TE_{220}-mode slotted SIW array	8×8	N.A./ 64	~22.3	~0.9	25.3
[14]	95	9.1λ ×11.9λ	TE_{560}-mode slotted SIW array	20×24	41.7/31.5	~6.3	~10	26.39
[4]	120	28.4λ ×28.4λ	Slotted waveguide array (Diffusion bonding)	32×32	80/78.7	~12	~2.1	39.1
[5]	140	16λ ×16λ	Slotted waveguide array (Diffusion bonding)	16×16	83/43.12	~15.1	~4	31.7
[6]	140	11.1λ ×9.63λ	Slotted SIW Array	4×4	55**/N.A.	~19.8	~3.8	16.3
[7]	140	5.04λ ×7.05λ	TE_{20}-mode Slotted SIW array	8×8	34/30	~15.2	~3	21.3
[8]	140	4.41λ ×3.95λ	TE_{340}-mode Slotted SIW array	8×8	59.2/51.1	~10.7	~3	20.5
This work	**140**	**5.26λ ×6.16λ**	**Slot waveguide array with VEWs**	**8×8**	**93.4/73.2**	**~10.2**	**~0.5**	**24.59**

Note: (1) The radiation efficiency is calculated as the ratio of measured gain to simulated directivity. (2) The aperture efficiency is $\frac{G\times\lambda^2}{4\pi A}$, where A is the radiation aperture area, λ is the wavelength, and G is the measured gain. (3) ** Simulated results.

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